TECHNOLOGIES FOR MARS EXPLORATION AND SAMPLE RETURN

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ABSTRACT

A comprehensive program of robotic Mars exploration is being undertaken in order to address important scientific questions, to investigate whether or not life exists or ever existed on Mars, and to pave the way for eventual human presence. The program, which is likely to include establishing robotic outposts, will require many technical advances. This paper briefly describes key missions in the Mars exploration program, including robotic outposts, and discusses near- and far-term technologies needed for their implementation.

INTRODUCTION

The first decades of the new Millennium will see a vigorous program of robotic Mars exploration, undertaken both for compelling scientific reasons as well as to pave the way, over the long term, for human missions and potential human habitation. The program will be strongly international in character.

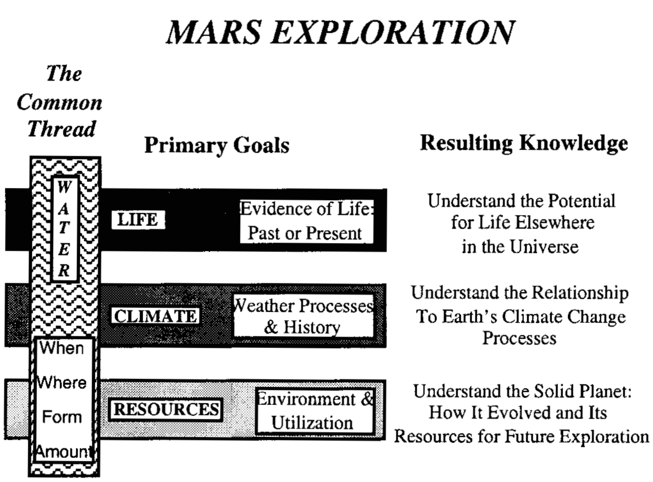

Figure 1. Mars Exploration Scientific Objectives

The program's principal scientific objectives, as shown in figure 1, are to look for evidence of past or present life, to understand Martian weather processes and history, to understand how the planet evolved physically, and to locate potentially useful resources. The common thread among these is water: How much existed, when, where, and in what form? In addition to remote sensing, answering these questions will require surface and subsurface sampling, in-situ analysis, and returning samples to Earth for analysis in terrestrial laboratories.

As currently envisioned, the exploration strategy begins with a series of robotic missions which gradually evolve into the sustained presence of robotic outposts. The early missions will perform science investigations, acquire and return samples, and will provide engineering data on system and technology performance in the Martian environment. They will also establish communication and navigation capabilities and will make it possible to select promising sites for additional exploration, to refine and optimize mission and system designs, to locate potential resources, and to begin the process of selecting landing sites for eventual human missions. Martian robotic outposts will provide more intensive scientific investigation and will begin to put in place the infrastructure needed by both robots and humans, including power and communication systems, shelters, and facilities for using indigenous resources.

In addition to being scientifically compelling, Mars missions must be good investments, employing innovative new technologies that might prove useful on Earth, and must be engaging to the public. They must also be accomplished within tightly constrained budgets and must neither put the terrestrial biosphere at risk nor contaminate Mars with terrestrial biogenic material, since such contamination would call into question scientific findings indicative of past or present Martian life.

Mars exploration, including returning samples to Earth and constructing robotic outposts, will require advances in a number of areas including sample acquisition, preservation, and containment as well as robotics, instrumentation, control, and vehicles for Earth re-entry. This paper describes some of the required technologies as well as technologies that would be significantly enhancing. It closes with suggestions on potentially useful technologies for future missions.

This paper represents a snapshot of an extraordinary, dynamic work in progress. It is based on review presentation materials and daily interactions with individuals at the Jet Propulsion Laboratory who are actively implementing the NASA portion of the Mars exploration program.

MISSION PLANS

The current form of the overall Mars exploration roadmap is shown in figure 2. Under the Mars Surveyor Program, NASA is in the process of implementing missions with launches scheduled in '01, '03, and '05. These missions are being closely coordinated with the ESA/ASI Mars Express, CNES Sample Return Orbiter and NetLander, and the ESA/BNSC Beagle Lander missions to derive maximum programmatic and scientific benefit. Missions for launch opportunities beginning in '07 are still under study and will naturally depend upon results of earlier missions as well as evolving priorities.

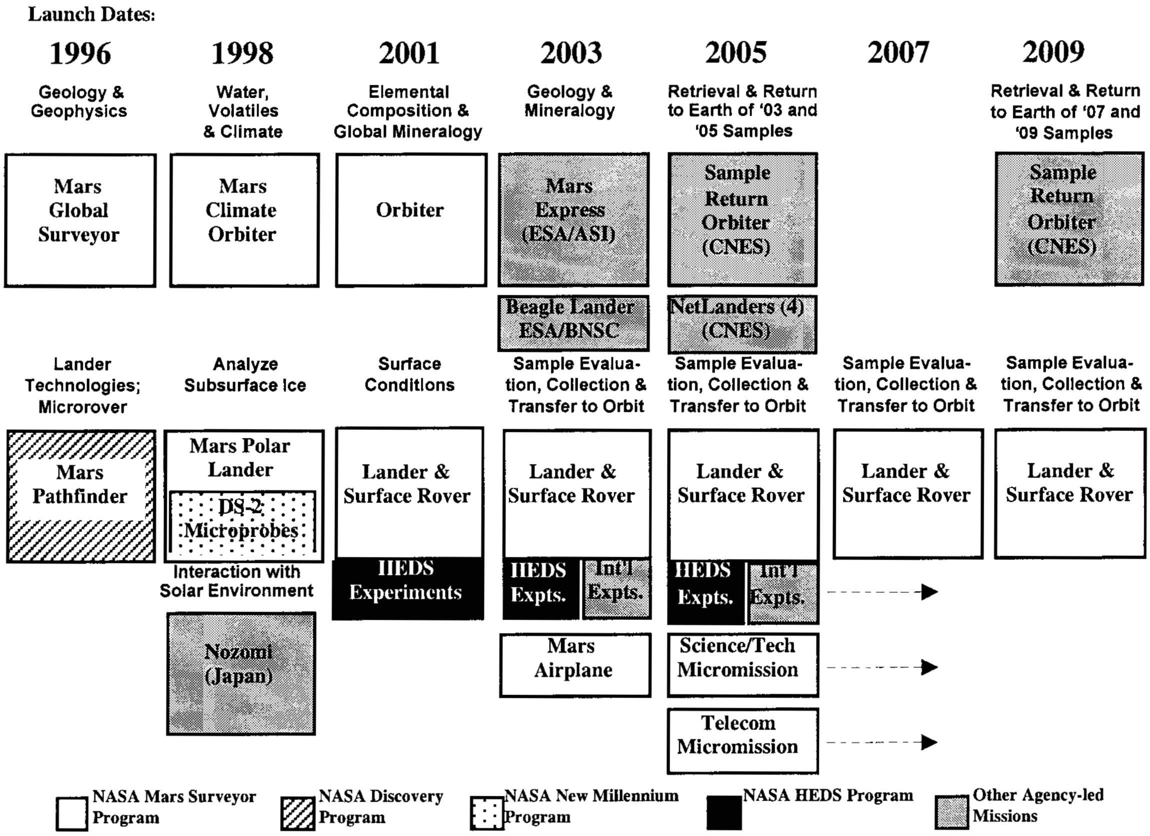

Figure 2 Mars Exploration Roadmap

Mars Surveyor Missions

Mars Surveyor '01

The '01 Mars Surveyor mission, which includes both an orbiter and a lander, is now in the implementation phase. The lander includes a manipulator arm similar to the Mars Surveyor '98 Polar Lander MVACS arm as well as a rover (Marie Curie). The rover is nearly identical physically and operationally to Sojourner, the Mars Pathfinder rover, but with significantly improved navigation accuracy achieved by upgrading accelerometers and gyro circuitry. Instead of using ramps, Marie Curie will be deployed by the robotic arm. The arm will also be used to supply Martian soil to lander-mounted experiments.

In addition to investigating geology, mineralogy, elemental composition, and the radiation environment, Mars '01 will include HEDS (Human Exploration and Development of Space) experiments. These experiments are designed to characterize Martian dust and to assess potential hazards to humans, the compatibility of the Martian environment with engineering materials and systems, and the feasibility of producing propellant from the Martian atmosphere.

Mars Sample Return

The Mars Sample Return (MSR) mission, which launches landers in '03 and '05 and an orbiter in '05, will return Martian samples to Earth for analysis. A mission timeline is shown in figure 3.

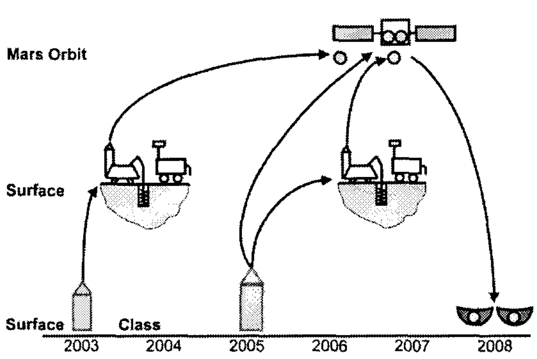

Figure 3. '03 –'05 MSR Mission Timeline

In addition to ground support and operations, other major elements of the MSR mission include the Landers and Rovers with their manipulators, drills, and instruments, and the solid-fuel Mars Ascent Vehicle (MAV). Additional major elements are the Sample Transfer Chain (STC), the Earth Entry Vehicles (EEVs), and the French-supplied Sample Return Orbiter (SRO), which carries the sample capture system, and the EEVs. Finally, there is also an extensive planetary protection element that is addressing new approaches to cleaning and sterilizing the flight hardware as well as sample containment and operations strategies that will minimize the probability of sample contamination.

Several of these elements represent significant advances over current practice and will be described briefly below.

Each lander will carry a surface rover (Athena) with a comprehensive sampling and analysis suite as well as a MAV. The landed system with the MAV and rover is shown in figure 4. Upon landing, the rover will descend the deployment ramps and, under direction of terrestrial scientists, move around the vicinity of the landing site performing in-situ analysis and gathering representative samples.

When sampling is complete, the rover will return to the lander, ascend the deployment ramps, and, using a docking block and contact sensor to verify position, deposit its samples in a canister within the MAV fairing. Samples will also be gathered by a lander-mounted drill, supplied by ASI, the Italian Space Agency. The drill will deposit its samples directly into the MAV.

When the samples have been deposited, the rover will move to a safe location, whereupon the MAV will be launched, carrying the filled canister into orbit. Once in orbit the canister will be hermetically sealed and jettisoned from the MAV. Samples from the '03 launch will be placed in orbit as soon as sample acquisition is complete, remaining in orbit until rendezvous and retrieval in '07 by the CNES-supplied Sample Return Orbiter, which will be launched in '05. Samples from the '05 lander launch will be also immediately be placed in orbit for retrieval once sampling is complete. Under guidance from on-board LIDAR and each canister's homing beacon, the SRO will rendezvous with and retrieve each canister in turn, stowing them in separate Earth Entry Vehicles (EEVs) for return to Earth in '08. The MSR mission ends with the EEVs' landing.

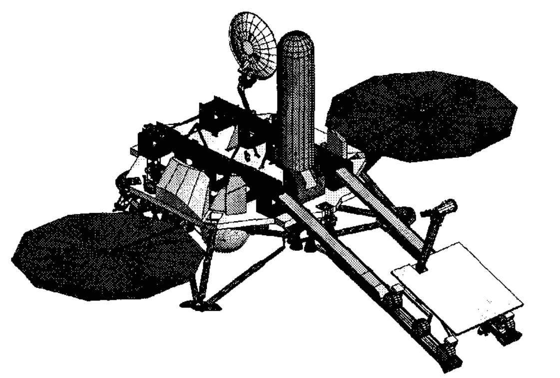

Figure 4. MSR Lander with MAV in Launch Position

The landed samples will be handled under a mission structure separate from MSR. The sample-handling mission will involve appropriate health and security agencies to assure there is no biological hazard. Landed sample handling will involve acquiring the canisters in their containment vessels, quarantine, curation, and eventual dispersal to research institutions. Proposals to acquire samples will be subject to scientific peer review.

The MSR mission, which will also include HEDS experiments that are yet to be selected, is now in the preliminary design phase. The preliminary design review is scheduled for December 1999.

Mars '07-'09

The '07 and '09 Mars Surveyor missions are in the design study phase. It is likely that they will be similar to the '03-'05 MSR mission, but with updated technology for improved mission performance. It is also possible that they may be the first robotic outpost missions.

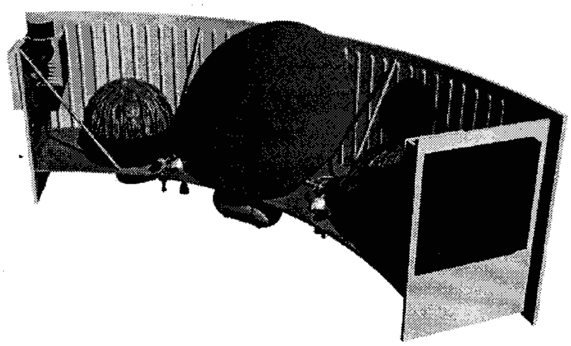

Figure 5. Mars Micromission Bus Concept

Micromissions

Micromissions, which will be launched as auxiliary payloads on commercial space launches using a common, therefore inexpensive, bus, are being planned to reduce the cost of access to Mars. A bus concept is shown in figure 5. Specific micromissions have not yet been selected, but possibilities include a Mars Airplane in '03 to commemorate the hundredth anniversary of the Wright Brothers' pioneering airplane flight and science/technology or telecom missions in '03 and '05. Telecom missions are particularly attractive, as they will provide telecommunication assets as well as satellite-based navigation capabilities for future Mars missions and robotic outposts.

Robotic Outposts

Robotic outposts represent the next stage of Mars exploration. They will constitute the beginning of a sustained, continuous presence on the planet. They will function as scientific research stations as well as bases for finding and exploiting water and other useful resources. They will also emplace infrastructure needed to support both robotic and human activity, thus serving both to expand scientific activity and as a beachhead for eventual human presence. They will continue in operation when humans arrive, providing essential support and assistance when needed.

Outposts will ultimately occupy numerous sites and must be periodically re-supplied. They will be remotely managed, but not directly controlled, from Earth, and will include versatile robots and robotic devices that are able to use tools, cooperate weakly or strongly, and handle the many mundane tasks involved in construction, maintenance, emergency response, and operation. Outpost robots must be capable of some degree of self-, or mutual repair, perhaps through module replacement. Figure 6 shows an artist's concept of an initial outpost.

Finding and exploiting useful resources, especially water (or hydrogen) for fuel and propellant production and, perhaps, for manufacturing simple building materials, is both scientifically interesting and critical for sustained outpost activity and human presence. The ability to produce basic commodities from indigenous resources will free re-supply flights to carry high-value items such as computers, circuit modules, instruments, and precision mechanical components that will not be locally available. Thus initial outposts will support a comprehensive program of surface, subsurface, and atmospheric exploration to assess resource availability.

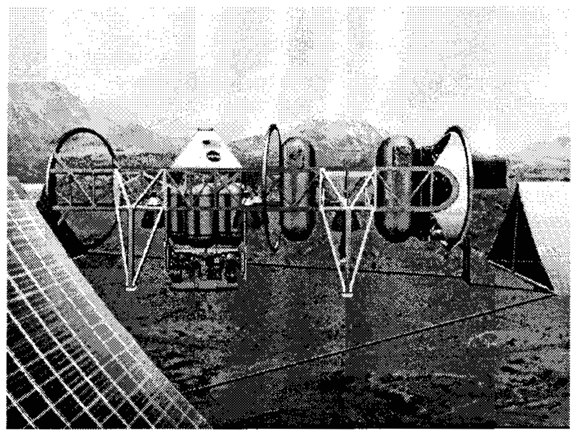

Figure 6. Initial Robotic Outpost. An ISRU station with rover is shown.

NASA is now seriously studying various approaches to outpost implementation. The exact form of initial outposts and the roadmap for their implementation is not yet determined, but initial thinking is along the following lines:

Candidate Outpost Timeline

2007 Outpost I

- Surface and subsurface exploration
  - Hybrid aerial vehicle for e-m sounding, microwave mapping, deployment of seismic stations and high-resolution surface mapping (morphology, mineralogy, magnetometry, etc.), possible sample collection--global range to map approximately two dozen possible landing sites

  - Surface rovers for long-range (500km) exploration & sample collection/caching
- Solar powered In-Situ Resource Utilization (ISRU) plant

2009 Outpost I

- Shallow drill
  - Solar powered with ISRU energy storage
  - 2 cm diameter bore, 200 m penetration
  - Characterize regolith, reach top of ground ice and confirm Clifford models
- Return of cached samples
  - ISRU direct return to Earth

2011 Outpost II

- Deep Drill (Delta 4 heavy)
- Nuclear power/ISRU plant with utility rover
- Replenish mobility elements

2013/15 Outpost II

- Human outpost pre-deployment and first crewed mission
  - ISRU water production
  - Hydrosphere sample analysis
  - In-person astronaut field exploration
  - Telepresence robotic surface and aerial exploration

This scenario is fairly aggressive in that it shows an initial human mission in 2013 or 2015.

CURRENT MISSION-TARGETED TECHNOLOGY DEVELOPMENTS

The Mars Surveyor Program has several mission-specific technology developments underway. Some are or have been mission-funded while the Mars Surveyor Technology Program supports others.

Mars '01

The '01 mission, as already described, will use a version of Sojourner, the Pathfinder microrover, with significantly improved navigation capabilities, as well as a robot arm similar to that on Mars '98. Other new technologies being flown are the Small Deep-Space Transponder (SDST) and phase-shift keying (PSK) on the UHF modem. Finally, the use of flexible solar arrays, a new high-density, high-efficiency power converter, and rechargeable lithium-ion batteries on the lander represent a significant advance in spacecraft power technology.

Mars Sample Return

Technology and advanced development efforts being undertaken for the Mars sample return mission include:

Mars Ascent Vehicle (MAV).

The MAV, which is a two-stage solid-fuel rocket with a mass target of 125 kg, will place the Mars samples in orbit. The first stage is guided, while the second is spin-stabilized. Selecting a solid-fuel vehicle rather than the original liquid-fuel concept, has permitted significant reductions in mass and complexity, and was instrumental in enabling the MSR concept to fit within mission cost and performance constraints.

Sample Transfer Chain (STC).

The sample transfer chain is the set of devices that handles and transfers the samples. It includes rover-mounted equipment, the canister assemblies, MAV-mounted equipment, and the Orbiting Sample Capture and Retrieval system (OSCAR), shown in figure 7, mounted on the Sample Return Orbiter. Once a canister is filled, sealed, and on orbit, it is called an orbiting sample (OS).

Samples enter the STC when they are initially acquired. Rover-acquired samples will be placed in individual sample containers and stowed in a rover-mounted sample cache. When sampling is complete and the rover is positioned over the MAV, which is horizontal at this stage, the fairing tip opens and the cache of samples is transferred. The fairing, which is also a bioshield, contains the unsealed canister. The canister lid is attached to the fairing tip; the canister itself is attached to the MAV structure. Samples acquired by the ASI-supplied, lander-mounted drill will be deposited in the MAV by the drill itself in a separate sequence.

When the samples have been deposited, the fairing is closed, the rover backs away, and the MAV is erected and launched.

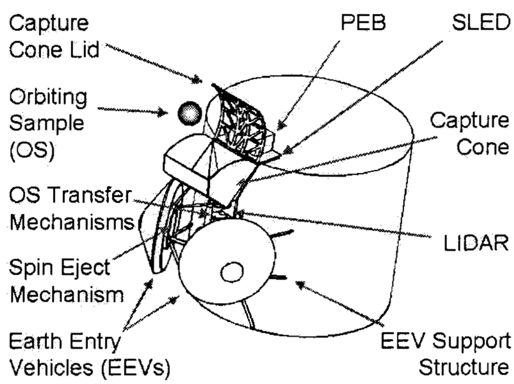

Figure 7. Orbiting Sample Canister Capture Mechanism

As mentioned above, meeting scientific requirements and protecting the Earth's biosphere from possible pathogens requires that the samples be hermetically sealed inside the canisters and that the canisters' external surfaces, as well as the seam area, be free of contamination by Martian material. The canister sealing approach being developed for MSR is an explosive welding process that simultaneously seals the canister, expels any contaminants from the sealed surface, and cuts away the fairing, leaving a sealed canister with a contamination-free external surface that meets the required class V cleanliness requirements. This is done after the canister has left the atmosphere to avoid recontamination by Martian dust. The process is robust in that unsuccessful sealing and cutting will result in the fairing's remaining attached to the canister making acquisition and retrieval of a potentially hazardous canister impossible. Since the canisters will contain a radio beacon and will be covered by solar cells and retroreflectors to permit their acquisition and capture, the explosive welding and cutting process is being designed to minimize damaging shock levels.

On-Orbit Rendezvous and Sample Retrieval

The Sample Return Orbiter must rendezvous with and capture the orbiting sample canisters. The capture mechanism is shown in figure 7. The radio beacon aboard each canister, powered by solar cells, will permit long-range direction finding and initial approach. When the orbiter is sufficiently near the canister, a lightweight laser ranging instrument now being developed will use signals reflected from the canister to determine its precise range and heading. The ranging instrument, which is being designed to apply to a wide variety of solar system missions, including potential uses in landing hazard avoidance, will be bore-sighted with the sample capture cone. The range and location information will be used with terminal guidance algorithms, also under development, for closed-loop terminal rendezvous and capture. Capture must be accomplished precisely, since slight misalignments may cause the canisters, which may be spinning, to bounce off the capture mechanism in uncontrolled directions.

Once captured, the sample containers are transferred to individual Earth Entry Vehicles and thermally sealed inside impact-resistant containment vessels for return to Earth.

Athena Rover

The rover is shown in figure 8. It will weigh about 72 Kg, and will be about a meter wide, 1.3 meters long and measure 1.5 meters from the ground to the top of the (extended) camera mast. It will carry a small manipulator arm with five degrees of freedom as well as radioisotope heater units (RHUs) to handle low nighttime temperatures. Dumping waste heat is a potential problem at midday. Rechargeable lithium-ion batteries and solar cells will provide power. It will not carry a nuclear power source.

The rover-mounted drill has four internal degrees of freedom and two positioning degrees of freedom (lateral motion and pitch). It has force and torque sensors for drill contact and torque and a position encoder on the motor. If the drill jams, the drill may be reversed, the bit may be released, or the drill stem itself may be released.

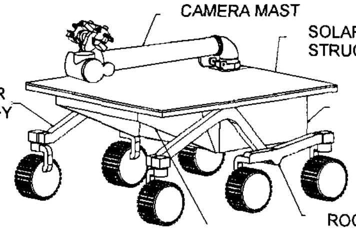

Figure 8. Athena Rover

Rover operation will be similar to that of Pathfinder's Sojourner in that mobility targets will be designated by terrestrial operators. Navigation will use odometry, state sensing, and a sun sensor. While automatic low-level reflexive behaviors like obstacle avoidance during traverses will exist, autonomy will be limited. The baseline approach is to use ground command cycles as needed to achieve positioning objectives like instrument placement, ascending ramps, and drilling. For such maneuvers the rover will perform a pre-positioning step near the designated target location and request ground confirmation before proceeding. There will nominally be one command uplink a day, but the mission may use quick confirmation cycles since there are six hours' communication time available.

The '03 rover will travel about 1 km (total distance), while the '05 rover will travel 5 km. Maximum radial distances from the lander will be about 100 meters.

Rather than relying exclusively on lander-based imagery, as was the case with Sojourner, a capability for using rover-based imagery for terrain-based localization is being developed. This will lay the groundwork for rovers that can operate out of line-of-sight of the lander and conduct long-distance traverses, capabilities that will be needed for robotic outposts and future missions.

While on-board image processing for autonomous image-based mobility is not baselined, the '03 and '05 rovers have a significantly more powerful sensing, control, and computational environment than Sojourner and Marie Curie, including a 10 MIPS R3000 processor with significant memory. The system also includes thirty motor controllers (including support for encoders, current monitors, and selected potentiometers), and fifty temperature sensors.

Performance-improving technologies under development that are not yet baselined for the '03-'05 rovers include:

- Increased autonomy for determining and executing sampling and instrument-placement sequences
- Closed-loop mobility for traverses and ascending the lander ramps using image processing
- Active control for rover-mounted drills to compensate for rover compliance

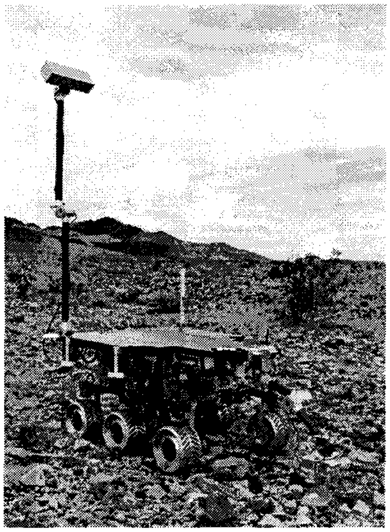

Figure 9. FIDO tests at Silver Lake, California, April 1999

These technologies, along with miniaturized flight-like instruments, are being integrated on the FIDO (Field Integrated Design and Operations) rover system and tested in extensive field trials (figure 9). This testing has proved to be invaluable in evaluating instruments, software, and operational techniques, and in training science teams in rover operations.

Planetary Protection Technology

Recent tests at JPL indicate that existing NASA spacecraft cleaning procedures and assay techniques, which can be extremely expensive and difficult to implement, cannot meet the stringent requirements of Mars Sample Return missions and their life detection experiments. Existing techniques leave a great deal of biochemical residue and do not appropriately account for the fact that the great majority of microscopic organisms are not culturable. Accordingly, work is being done on improved methods for cleaning, sterilization, and assaying surfaces for contamination. Work on cross-contamination modeling and defining workable, scientifically acceptable cleanliness and assay standards is also underway. Cross-contamination modeling aims to describe the ways particulates, likely residence sites for microbes, can move from surface to surface under environmental influences. It is especially important for designing sampling devices and operational sequences, but is analytically intractable due to the complexity of real environments. Accordingly, a pragmatic, empirical approach is being adopted that, it is believed, will result in practical design approaches and guidelines.

Micromissions

Since reducing mass is considered to have the highest direct payoff for micromissions and propulsion systems comprise a significant portion of spacecraft dry mass (~30%), the Mars Surveyor Technology Program is seeking to reduce propulsion system mass by developing lightweight tanks and propulsion components. Development is aimed at micromissions, but the technology will be widely applicable. Tank mass reductions in fiber over-wrapped tanks with ultrathin aluminum liners have exceeded 50% compared with Titanium tanks, with equivalent performance. Mass reductions in propulsion components--latch valves, check valves, service valves, regulators, and filters--are between 50% and 90%. This has been achieved through careful design and material selection and adopting the strategy that components like service valves can be redesigned as separable ground and flight parts. The parts not essential in flight are left on the ground as service equipment rather than being flown. As spacecraft become smaller these mass reductions will have significant system-level effects.

CURRENT TECHNOLOGY EFFORTS TARGETED TOWARD FUTURE MISSIONS

Other technologies important for future missions being addressed by the Mars Surveyor Technology program include instrument miniaturization, precision landing, and landing hazard avoidance. Miniaturization, which is critical for the long-term success of the Mars exploration program and will have significant terrestrial benefits, means that more instruments can be flown for a given launch vehicle capacity, thereby increasing science data return. Precision landing, which involves significantly reducing the size of the landing error ellipse, is important for minimizing surface mobility requirements. In turn, this will make it easier and cheaper to reach previously identified sites for exploration, exploitation, and resupply. Landing hazard avoidance is a risk-reducing strategy. It becomes an important issue when landing at sites that are morphologically complex to avoid disasters like falling into depressions or landing on rocks, thereby risking mission failure due to the lander's falling over. Hazard avoidance requires the real-time analysis of rangefinder or optical images, and generation of control commands, which require, in turn, considerable on-board computational resources. Since the mass penalty for carrying extra maneuvering fuel is high, it is important to make hazard avoidance decisions as early as possible in the descent. This can be a challenge since resolution of surface features from high altitudes can be poor.

ENABLING TECHNOLOGIES FOR ROBOTIC OUTPOSTS AND FUTURE MISSIONS

What is really needed to make extensive robotic or human presence on Mars feasible is making missions much cheaper. There are several ways to approach this. One strategy is to improve system components by reducing requirements for such resources as mass, power, volume, and data rate, while improving component and system performance. Another is to develop and land infrastructure elements for producing needed resources, such as propellants and, ultimately, breathable air, from local materials, ensuring that resources are available in sufficient quantities. Still another, longer-term, strategy is sending information and basic infrastructure elements to Mars, producing mission and additional infrastructure hardware as well as consumables from local materials. The latter strategy amounts to setting up a largely self-sufficient Martian economy and will require finding and exploiting water and suitable minerals and constructing extraction, refining, and manufacturing facilities. Pursuing all three strategies will be beneficial, but doing so will require significant technical advances. The list below identifies some of the principal technical capabilities needed in the indicated areas.

It is worth remembering that there are usually several approaches to solving problems. System lifetime, for example, can be increased by developing longer-lived, more reliable components, or by making them easier to maintain. Likewise, in environments where atmospheric pressure is low, the need for evacuating sample chambers for electron microscopy might be circumvented by packaging the electron source and optics within terrestrially-evacuated chambers that are sealed with electron-transparent membranes, thus removing the need for vacuum pumps.

Robotics

- Science investigations
- Surface/subsurface sample acquisition including deep subsurface access
- Site preparation/excavation
- Asset emplacement and erection
- Construction
- Maintenance, housekeeping, repair, including robot system repair and dust removal
- Robotic resource extraction: Drilling, mining, hauling, refining

Intelligent Systems

- Data mining--reduces cost of science data analysis
- In-situ science data analysis--reduces downlink capacity requirements and reduces mission execution time since operational decisions based on scientific results can be made locally
- Outpost management and control

Mechanisms, Structures, and Materials

- Inflatable structures and structural elements
- Lightweight components and structural elements
- Survivable elements and materials: thermal, radiation, lifetime, wear, corrosive environments
- Multifunction structures with embedded sensors and actuators
- Micro Electromechanical Systems (MEMS)-based components for microspacecraft
- Thermal control

Miniaturization and Avionics

- Microavionics: microgyros, microaccelerometers, system state sensors
- High-performance, low-power computing
- Electronic and electro-optical materials
- Fiber optics
- New approaches to high-density component interconnection

Instruments

- Ultraminiature multichannel instruments and support equipment (pumps, valves, reagent handling, etc.)
- Smart instruments for automating field geologist functions

In-Situ Resource Utilization

- Raw material refining and processing techniques
- Novel in-situ manufacturing techniques, especially with multipurpose capabilities
- Practical, low-cost fabrication materials made from locally-available resources
- Propellant and fuel production

Power Systems

- Surface power generation, management, and distribution systems (nuclear, solar, Areothermal, wind)
- On-board robot power systems including use of fuel cells for applications requiring high-power density
- Energy storage systems including batteries

Space Transportation

- High-performance, low-cost space transportation systems
- Lightweight propulsion technology
- Autonomous rendezvous, docking, and transfer
- Lightweight aerocapture and Earth entry systems
- Precision/safe landing

Planetary Protection

- Effective, automated means for space system bioload reduction and verification
- Sample isolation techniques

Telecommunications

- High data rate communication including optical communication
- Communication network; solar system internet
- High-efficiency communications components

Mission Implementation

The above items have concentrated on flight and landed systems. Reducing the cost and time associated with mission implementation (engineering, integration, testing, operations, and management) is also critical, however. Effecting these reductions, which is already underway as we strive to meet stringent mission cost constraints, will be accomplished largely by developing improved information analysis and management systems, improved design, simulation, and testing environments, automated fabrication processes, and automated mission operations tools. New processes, materials, and flight system technology, however, will also play a significant role. Planetary protection costs are so high that developing automated, non-contaminating assembly and testing processes is particularly attractive. Finally, the cost and time associated with mission data analysis is significant. Computer-based analysis and data mining tools will be of significant benefit here as well.

These reductions will have a significant effect on mission-specific implementation costs as well as upon the cost of purchased items, such as launch vehicles as suppliers adopt engineering automation technology in an effort to remain competitive in the rapidly-changing global economy.

ROBOTICS AND INTELLIGENT SYSTEMS

Robotics is all about performing physical tasks. That is, bringing objects into prescribed mechanical states (position, force, velocity) relative to one another. Complex tasks, like building a structure, doing a geological survey, or overhauling an automobile, are composed of a large number of more elemental tasks like installing threaded fasteners. Elemental tasks, in turn, are composed of primitive actions like *move, twist, read reaction torque and fastener advance*, and so on. Primitive actions themselves are complex sensor-motor processes involving sensory perception and the control of multiple degrees of freedom. As an action proceeds, it is necessary to keep track of the temporal evolution of the sensory signatures associated with the action, note their deviations from expected behavior, and recognize and respond to errors.

Being able to execute primitive actions is necessary, but not sufficient. Complex tasks themselves, as entities, must be planned and managed. To be accomplished they must be broken down into appropriate sequences of elemental actions, which are broken down in turn into sequences of primitive actions. The primitive actions are then executed at the appropriate times. As a task is executed, its evolution must be monitored to ensure that it is proceeding appropriately. Recovery plans, which themselves become subtasks, must be generated and executed if it is not.

The greater a robot's ability to plan and execute tasks on its own and the greater its versatility--the ability to perform a variety of tasks--the greater its autonomy and utility. Autonomy is critical to achieve high mission throughput since relying on terrestrial intervention is extremely time consuming because of data rate limitations and signal latency. In addition to being able to perform individual tasks autonomously, it is also important for robots to be able to cooperate since complex tasks may require the coordinated efforts of many robots

Robotic rovers have already demonstrated their value in Mars exploration. Developing competent robotic assistants that can autonomously perform field investigations and provide and maintain infrastructure would improve mission performance even more, and is in fact essential for large-scale presence on Mars. A possible progress metric is comparing the complexity of standardized tasks that can be executed successfully to the number of bits that must be uplinked in order to accomplish the task. Cost is, of course, important as well.

While developing capable robots is attractive and critical, there are difficult issues associated with robotic autonomy: How do you make robots, which tend to be clumsy, repair practical items, especially when damage is involved, meaning that the affected parts do not correspond with database descriptions? How do you make robots that can repair themselves or each other? Where do you get the parts?

Making robots more capable and endowing them with enhanced intelligence and the ability to cooperate will require advances in the following areas:

- Spatial and logical reasoning, planning, diagnosis, episodic memory, modeling behavior of external agents including other robots
- Expanded sensory suites, machine perception including vision, and fusing information from different sensory modalities
- Sensor-motor control: closing task loops using perceived task parameters
- Novel approaches to space, surface, and subsurface mobility
- Robotic tool suites
- Developing robot configuration(s) and sizes for particular task classes
- Practical dexterity enhancement
- Dynamic stability
- Powerful on-board power systems
- Machine learning and adaptation
- The acquisition, organization, and retrieval of information
- Development of powerful hierarchical architectures that support the above capabilities.

The last item, architectures, which melds together the machine intelligence, machine perception, and control aspects of robotics, is critically important and has not received sufficient attention.

It is important to note that while a great deal of automation technology is realized through software, including representations and algorithms, the software must be executed in computing hardware and must make decisions based on sensory input and effect the world using actuators. Thus computer hardware, sensor, and actuator technology, including networking, electronics, and many other disciplines, is fundamentally enabling.

Intelligent automation technology, which has already had a significant effect on the world, will be broadly useful in many quarters including military systems and manufacturing, and even in such apparently fanciful areas as intelligent, interactive toys. It is difficult to overstate the profound effect that computing and the intelligent automation it enables will have on the course of civilization.

POTENTIAL TECHNOLOGY TRENDS

The technologies and technical needs discussed so far in this paper are largely extrapolations from the current state-of-the art. As is well known, it is nearly impossible even for experts to make accurate predictions about the timing and effects of scientific discoveries and technological innovations (so-called disruptive technologies). We can, however, identify some areas that might emerge as having important long-term effects even though they may now seem like science fiction:

- Nanotechnology
- Ultraminiaturization of instruments
- Quantum computing
- Molecular computing
- Optical computing
- Neurocomputing
- Buckyballs and buckytubes in materials and electronic packaging
- Quantum teleportation
- Applications of biotechnology and natural selection to the automatic creation of software
- Applications of biotechnology to complex self-assembling, self-repairing structures and systems

Many more items, of course, could be added to the list. Biology addresses problems far more complex than those historically addressed in engineering. Biological ideas, which are starting to emerge into the mainstream of engineering, may have a significant long-term role in the way we approach Mars exploration and many other aspects of economic activity. Similar remarks can be made about novel approaches to computing and quantum mechanics. It will be interesting to see what emerges from research laboratories.

SUMMARY

The early decades of the new millennium promise an extraordinary program of Mars exploration including returning samples to Earth, establishing the sustained presence of robotic outposts, and potential human missions. Technical issues as now understood are being addressed by engineers and scientists, but the long-term program will require major technical advances, especially in the areas of robotics, intelligent systems, and computing. Some of these advances will be stimulated by specific mission needs. Others will arise serendipitously from the exploration of new ideas in research laboratories.

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